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Electron Beam Welding of a Depleted Uranium Alloy to Niobium Using a Calibrated Electron Beam Power Density Distribution

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Introduction

Electron beam test welds were made joining flat plates of commercially pure niobium to a uranium-6wt%Nb (binary) alloy. The welding parameters and joint design were specifically developed to minimize mixing of the niobium with the U-6%Nb alloy. A Modified Faraday Cup (MFC) technique using computer-assisted tomography was employed to determine the precise power distribution of the electron beam so that the welding parameters could be directly transferred to other welding machines and/or to other facilities.

Procedures

Electron beam welding was performed at Lawrence Livermore National Laboratory using a 150 kV/50 mA Hamilton Standard welder (No. 175) fitted with a ribbon filament and an R-40 gun. A 10 mA, 100 kV sharp-focused electron beam was used to weld the parts in a vacuum chamber pumped down to 10^{-5} torr. The parts were located 7.0 inch below the top of the vacuum chamber, and the weld was made by moving the parts at a constant travel speed of 40 ipm under the stationary electron beam. The commercially pure Nb plate was received in the annealed condition and contained 10 ppm C, 95 ppm O, 35 ppm N, <5 ppm H, 400 ppm Ta, 15 ppm Fe, and 15 ppm Si, based on the mill analysis. The U-6%Nb alloy was acquired in plate form and had been heat treated for 2 hours at 200 °C; the composition of this plate was not measured.

In order to minimize mixing between the Nb and U-6%Nb, a weld joint design was developed with a 70°deg. angle to help match the natural wedge shape of the electron beam fusion zone to the U-6%Nb alloy that was being melted. In this design, the electron beam was concentrated on the U-6%Nb side of the joint to help mitigate the large difference in melting points between the Nb (2469°C) and U-6%Nb (1140°C). Figure 1 shows a schematic drawing of the joint and the location of the electron beam, which is offset 0.020 inch from the location where the Nb and U-6%Nb come together on the top surface of the plates. This offset distance was chosen based on the results of several practice welds, which showed that the molten U-6%Nb may not wet the entire Nb interface to the top of the joint if the beam is offset more than 0.020 inch from the interface with these welding parameters, and that undesired melting of the Nb occurred if the offset was less than 0.020 inch.

The power density of the electron beam was measured using a Modified Faraday Cup (MFC) device [1-3]. These measurements were made by deflecting the electron beam in a circular pattern over the top of the MFC. The MFC design contained 17 slits [3], one measuring 0.008 inch wide and the other 16 measuring 0.004 inch wide. Data was taken while scanning the beam over the MFC at 60 Hz and in a 25 mm diameter circle using the on-board deflection coils of the electron beam welder. Electron beam profile information was gathered as the electron beam passed over each slit by measuring the voltage drop across a 203.7 ohm resistor. Rapid data collection was performed using an analog-to-digital converter sampling at a frequency of 1 MHz. Figure 2 shows one of the 17 profiles taken, indicating that the data was very clean and virtually free of electronic noise. No filtering was required prior to tomographically reconstructing this data using the LLNL developed software written on LabView 5.0 [1,2].

Figure 3 compares the tomographically reconstructed power distribution of the electron beam both before and after the weld was made. Immediately before the weld was made, the beam was shown to have a nearly circular Gaussian shape, with a FWHM value of 0.206 mm, a FWe2 value of 0.338 mm, and a peak power density of 16.9 kW/mm^2. The electron beam was again measured immediately after the weld, showing that all parameters were within 2% of their initial values. This variation is considered to be within the accuracy of the present MFC diagnostic device and tomographic reconstruction methods.

Figure 4a shows a metallographic cross section made from the welded joint at low magnification. The weld is free of cracks, free of porosity, and the weld penetration exceeded the depth of the step by 0.014 inch. It is clear that the fusion line followed the 70 deg. angle of the original joint preparation on the Nb side of the weld, with minimal dissolution of Nb into the fusion zone. The entire Nb interface was shown to have been wet by the molten U-6%Nb alloy, leaving no undercut on the top surface of the weld joint. The final part could then be machined from the completely fused portion of the weld above the step in the joint.

Figure 4b shows a close up view of the Nb side of the fusion zone, indicating perfect wetting of the Nb interface by the molten U-6%Nb alloy. Dendritic solidification occurred on this side of the joint with epitaxial growth from the Nb base metal. Figure 4c shows a close up view of the U-6%Nb side to the fusion zone, indicating that the molten U-6%Nb alloy solidified in a cellular/dendritic mode with epitaxial regrowth from the U-6%Nb base metal. Future work is planned to study the mechanical properties of this joint.

Summary

High integrity electron beam welds joining commercially pure niobium to a U-6%Nb alloy were made without any special procedures other than to incorporate an angled joint interface to minimize mixing between the high melting point Nb and the U-6%Nb alloy. Computer assisted tomographic measurements were made on the electron beam to characterize its peak power density and power density distribution. Results showed that the electron beam had a nearly circular Gaussian shape with a peak power density of 16.9 kW/mm^2 and a FWHM value of 0.206 mm. Calibration of the electron beam makes possible the direct transfer of the electron beam welding parameters to other electron beam welding machines at other facilities.

Acknowledgments

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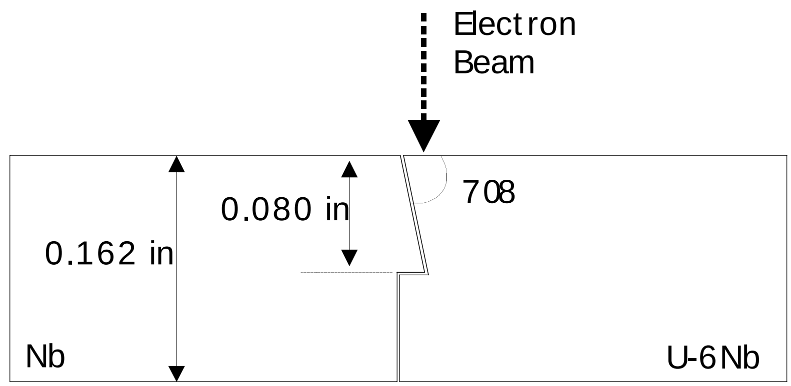


Figure 1: Schematic drawing of the electron beam weld joint design. The beam is offset 0.020 inch into the U-6%Nb alloy from joint interface on the top surface of the component.

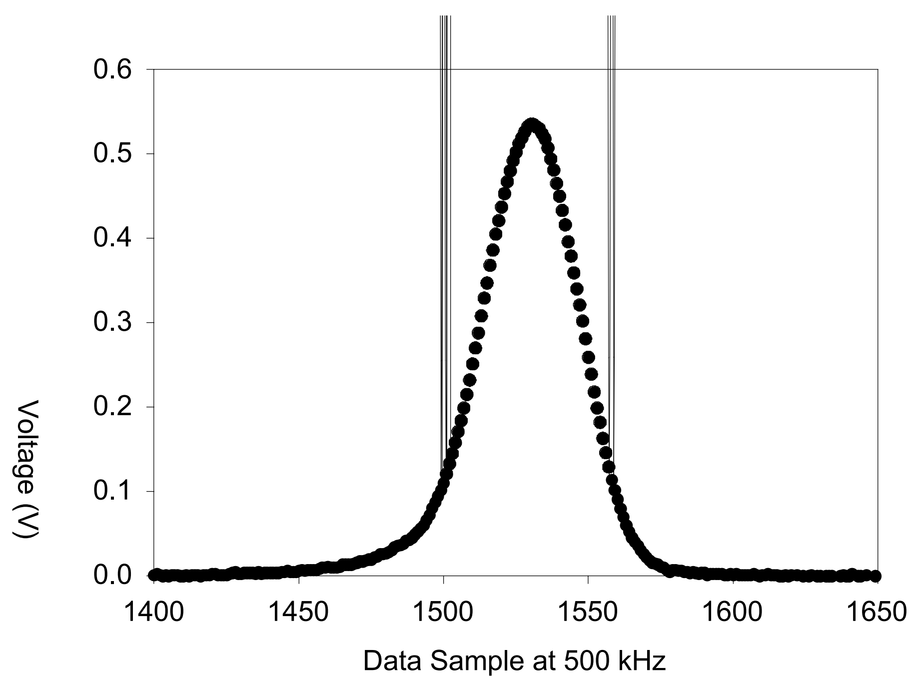
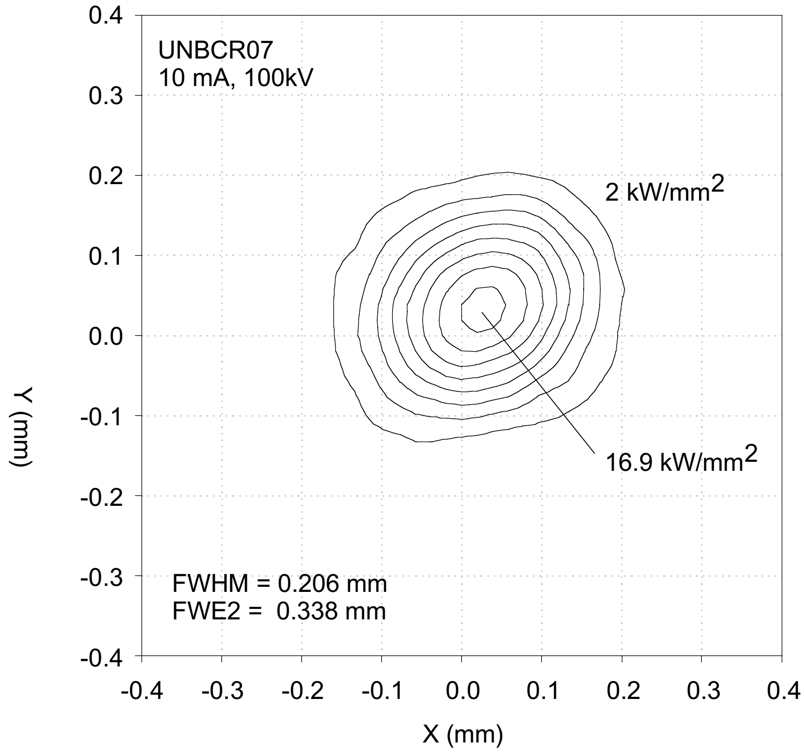


Figure 2: Raw data from the MFC showing one of the 17 electron beam profiles acquired for computer assisted tomographic reconstruction of the electron beam. Note the very smooth profile with minimal electronic noise.



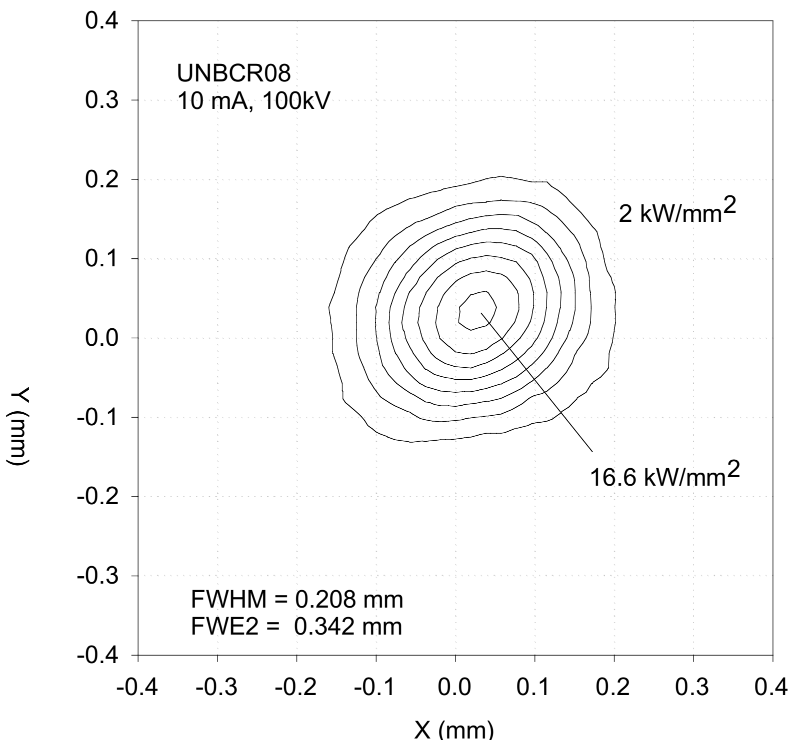


Figure 3: Tomographic reconstruction of the electron beam : a) immediately before the weld was made, and b) immediately after the weld was made.

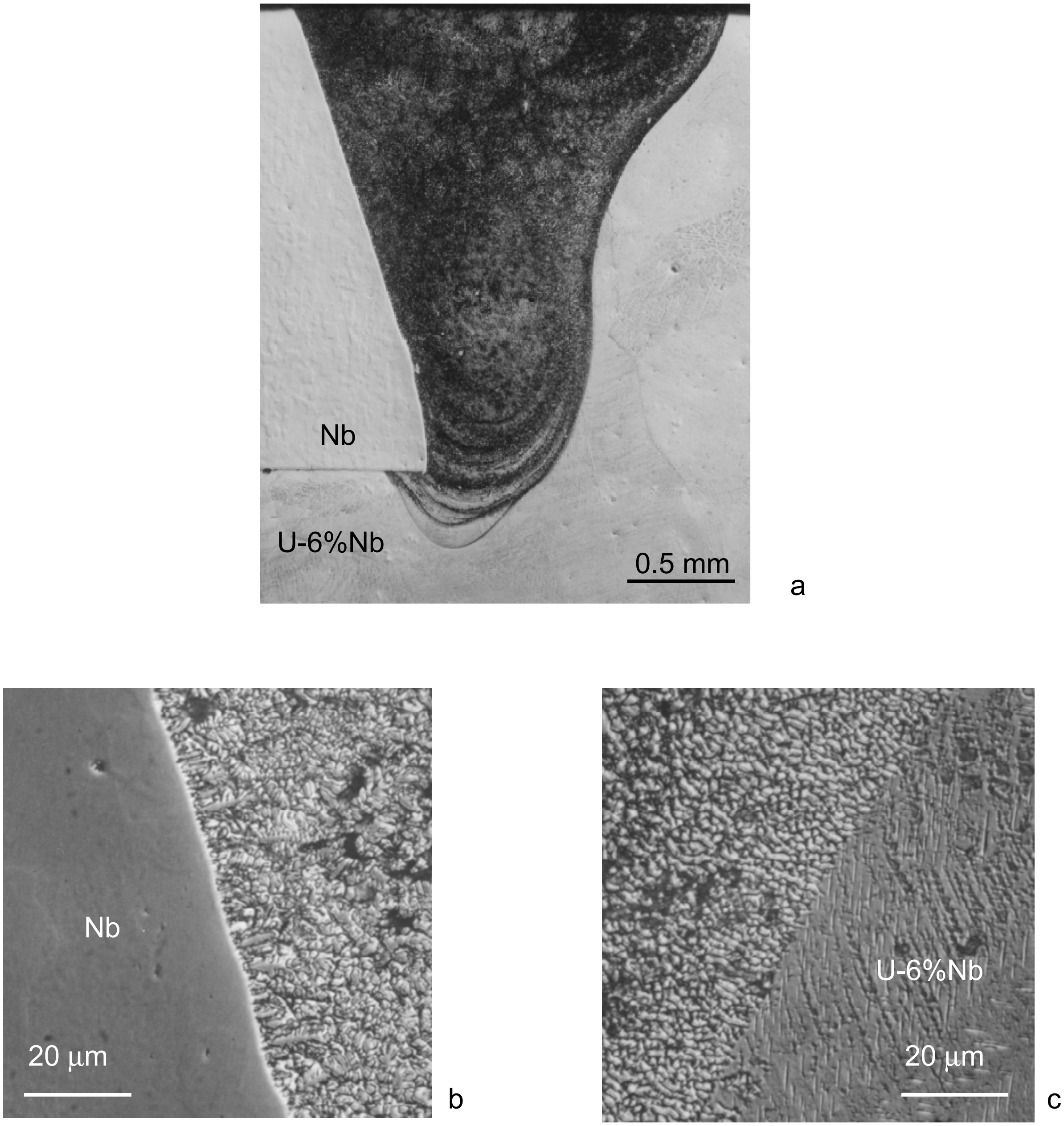


Figure 4: a) Optical metallographic cross section of the electron beam weld fusion zone at low magnification. The U-6%Nb alloy is on the right hand side of the micrograph, revealing a fusion zone shape consistent with that of a keyhole penetration mode weld. The Nb is on the left hand side of the micrograph, revealing the largely unmelted 70 deg. angled Nb-joint preparation. b) High magnification micrograph of the Nb side of the fusion zone, and c) high magnification micrograph of the U-6%Nb side of the fusion zone.